Temperature-Following Thermal Barrier Coatings for High-Efficiency Engines

June 21, 2018 - Project ID: acs123

Tobias Schaedler, Principal Investigator
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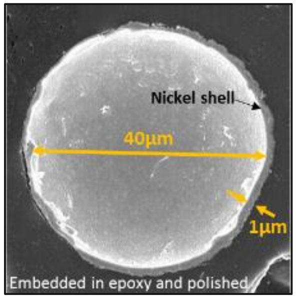

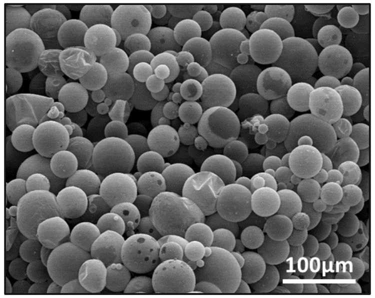

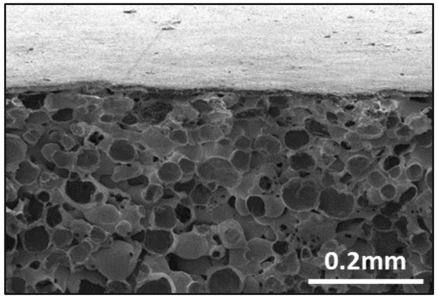

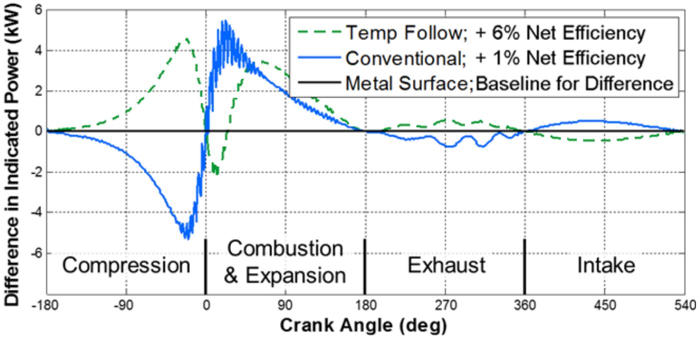

Team:

Tobias Schaedler, Christy Lihn, Scott Biesboer, Sloan Smith, Morgan Stilke - HRL
Peter Andruskiewicz, Russ Durrett, Paul Najt, Mike Walker - GM

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Program Overview

Prime Performer: HRL Laboratories (Malibu, CA)

Subcontractor: GM R&D (Pontiac, MI)

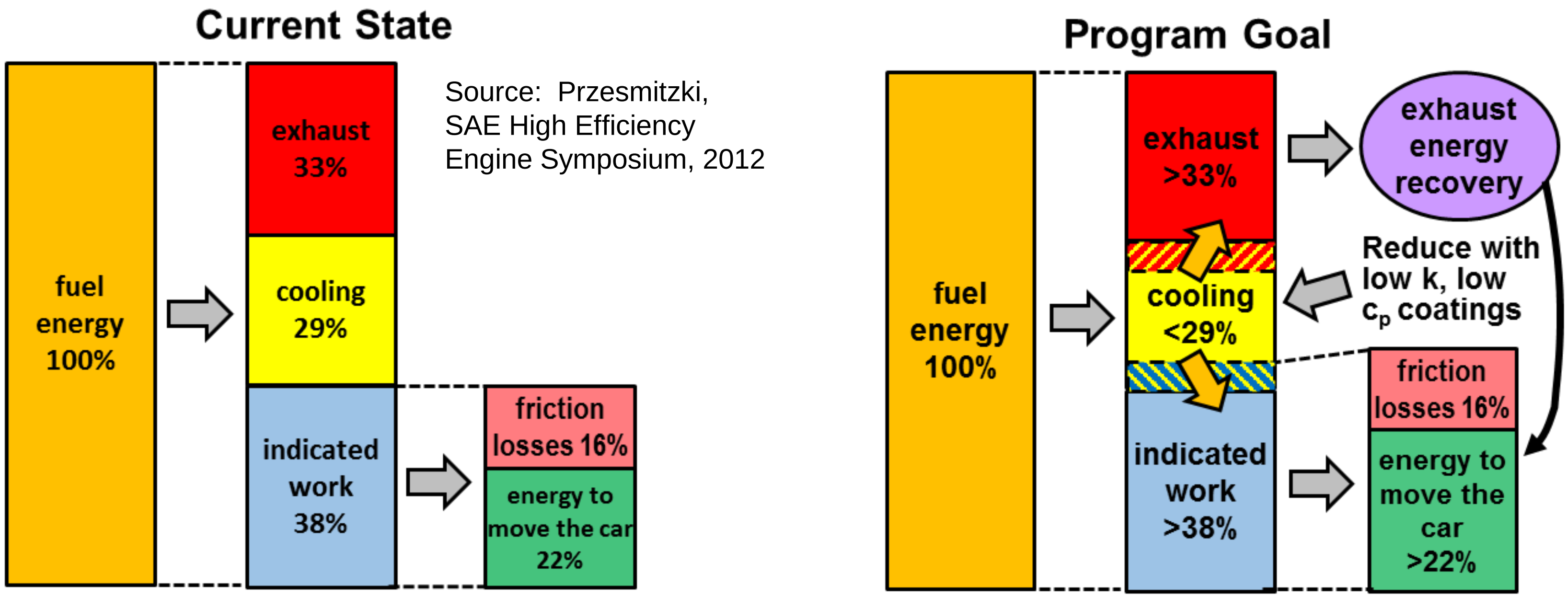
Scope: This project includes work to develop, implement and test temperature-following thermal barrier coatings (TBCs) that will decrease heat loss from the combustion chamber.

Barriers Addressed:
- Dilute Gasoline Combustion – Thermal Management
- Parasitic Loss Reduction and Waste Heat Recovery
- Dilute Gasoline Combustion – Knock Mitigation

Period of Performance: 1/1/2017 – 12/31/2019
- 3 budget periods of 12 months with go/no-go milestone after BP1 & 2

Award Amount: $2.8M (50% cost share provided by GM)
- $730k in 2017, $1,137k in 2018 including cost share

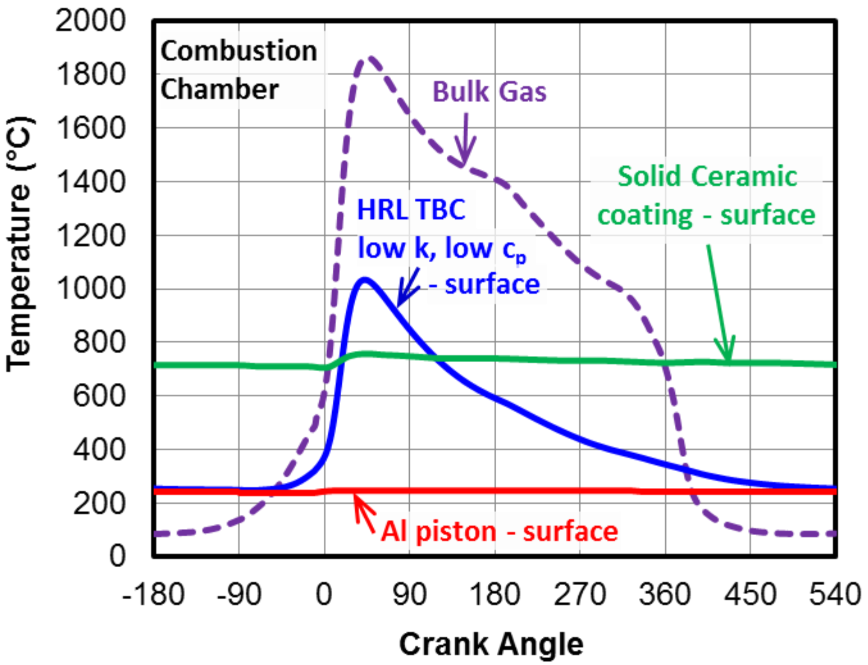
Objective / Relevance

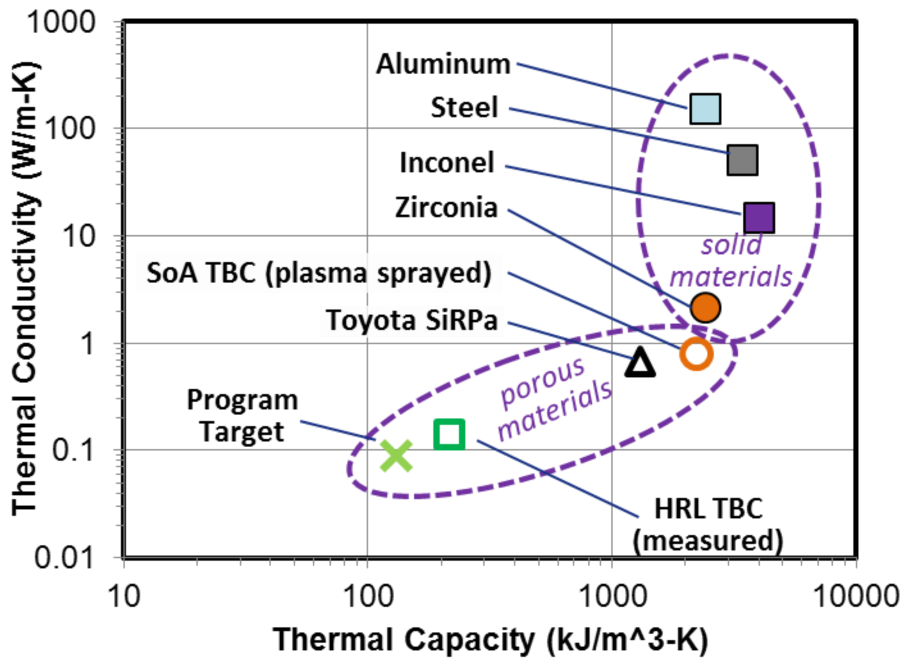


Objective: The objective of this project is to increase the efficiency of internal combustion engines by 4% to 8% with thermal barrier coatings within the cylinder and exhaust ports that add less than ~$250 in cost to a 4-cylinder engine. Benefits will be derived from:

- In-Cylinder Efficiency improvements through lower heat losses
- Increased effectiveness of exhaust energy recovery and aftertreatment with higher exhaust temperatures under highly dilute conditions
- Lower parasitic losses due to reduced cooling demands

Objective / Relevance





TBC must have low k and low c_p to follow the combustion gas temperature closely and reduce heat loss. This mitigates both knock tendencies and volumetric efficiency losses, unlike solid ceramic coatings with high c_p.

HRL's microshell TBCs exhibit 10X lower thermal conductivity (k) and heat capacity (c_p) than state-of-the-art materials. Further improvements will enable 4% to 8% efficiency gains and increase durability.

Project Milestones

Task	WBS	Subtask (Budget Period is first digit in WBS)	Budget Period 1 (2017) / Budget Period 2 (2018) / Budget Period 3 (2019) — Q1 Q2 Q3 Q4	Performer
0. PM	0	Program Management	D1 … D12	HRL
1. Modeling	1.1	Simulation of Coating Performance		HRL
	1.2	Simulation of Engine Performance		GM
2. Coating Development	2.1	Microshell Development	Microshells M1.2.1; Large-Scale Process M2.2.1	HRL
	2.2	Coating Process Development	Large-Scale Process M2.2.2	HRL
	2.3	Coating Surface Sealing	Large-Scale Process M2.2.3	HRL
3. Testing, Charact. & Analysis	3.1	Thermal Properties of Coating	k<0.2 cp<0.2 M1.3.1; k<0.1 cp<0.15 M3.3.1	HRL
	3.2	Permeability & Mechanical properties	0.001mD 200bar M1.3.2; 0.001mD 200bar M3.3.2	HRL
	3.3	Single Cylinder Engine Testing	>2% efficiency M1.3.3; >4% efficiency M2.3.3; M3.3.3; >4% & Durability M3.3.4	GM
4. Manufact. Readiness and Scale-up	4.1	Develop Supplier for Microshells	Cost Effective M3.4.1	GM & HRL
	4.2	Develop Supplier for Coated Pistons		GM & HRL
	4.3	Develop Supplier for Exhaust Ports		GM & HRL
	4.4	Develop Supplier for Coated Valves		GM & HRL

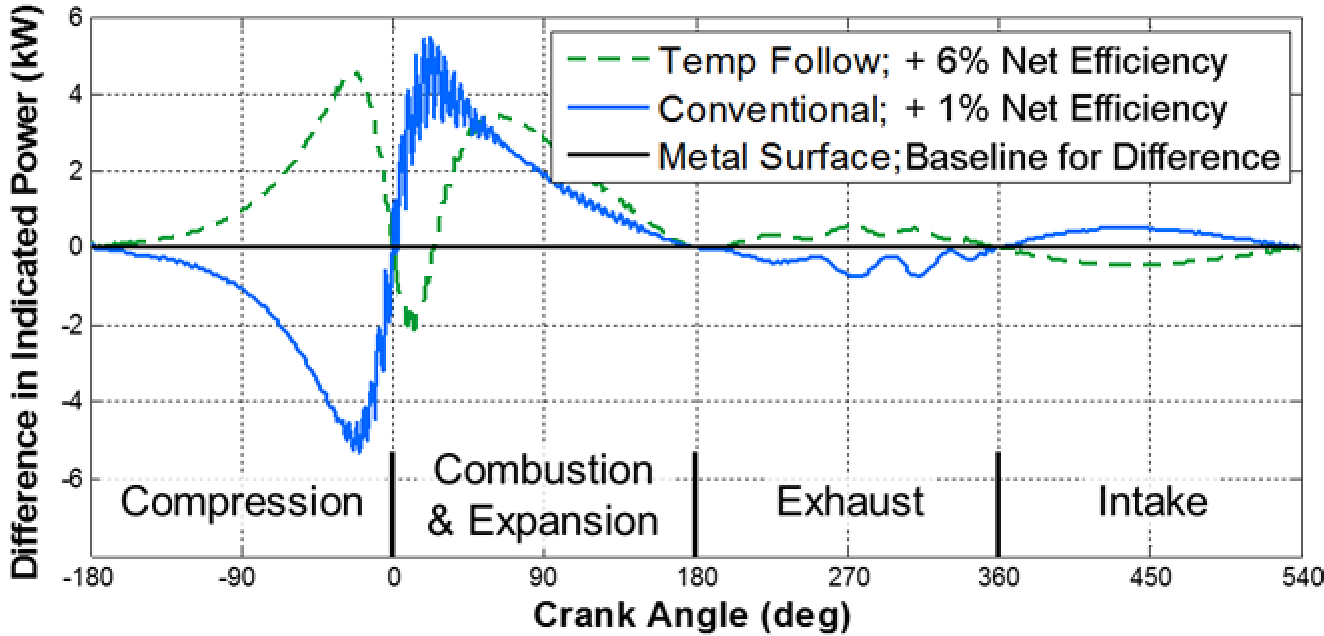
▲ = Milestone △ = Go/No Go ▲ = Deliverable

Approach

Temperature-Following insulation allows surfaces to stay cool during the intake and compression stroke, which will help volumetric efficiency and compression work. During combustion, the Temperature-Following coating surface can increase rapidly to provide insulation benefits.

Over the entire cycle, Conventional insulation's expansion benefits are negated by the increased compression work, while Temperature-Following shows improvements over Metal in compression & expansion.

This allows in-cylinder insulation to provide all the benefits of lower heat rejection, but with none of the volumetric efficiency or knock drawbacks.

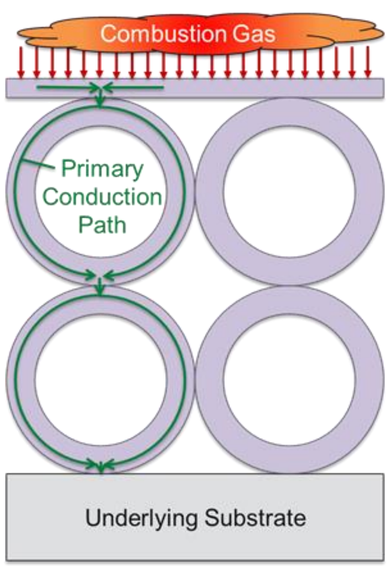


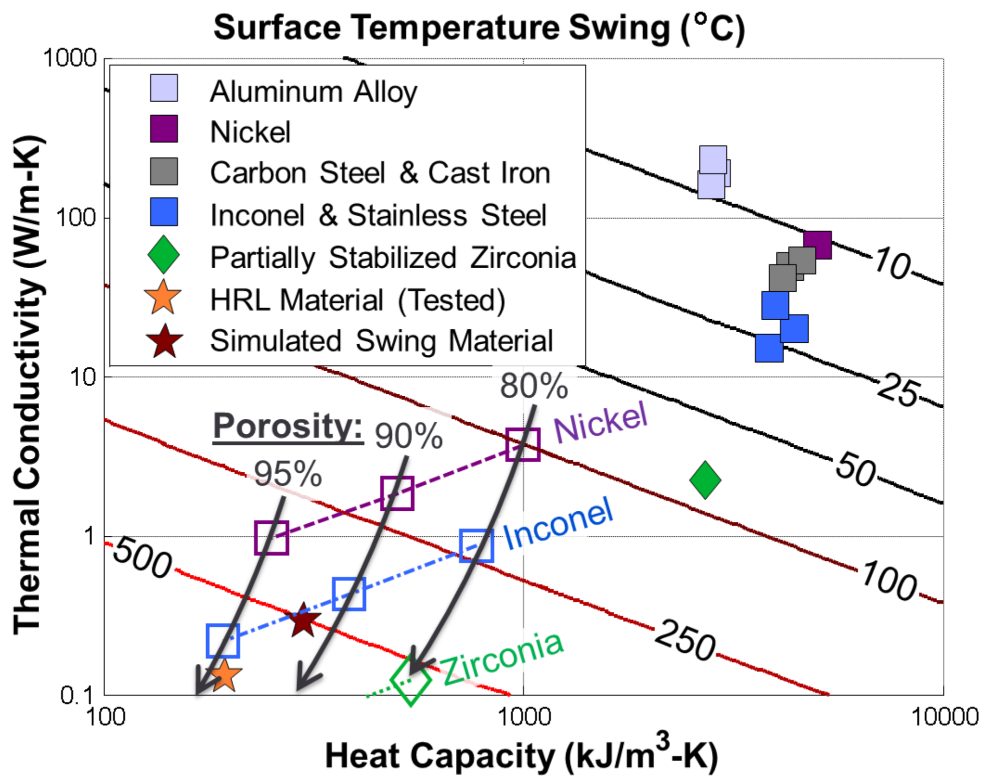
Approach

Thermal conductivity and volumetric heat capacity were independently varied to determine the material properties necessary for maximizing the temperature swing. High levels of porosity were determined to be necessary to decrease both the volumetric heat capacity (density) and the thermal conductivity.

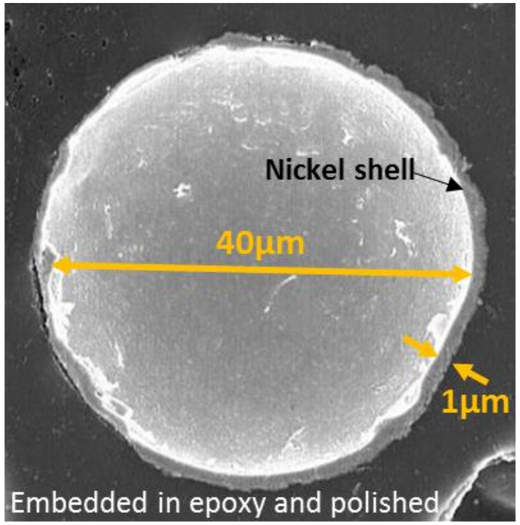
Estimated material properties for various solid materials and levels of porosity are overlaid on the plot.

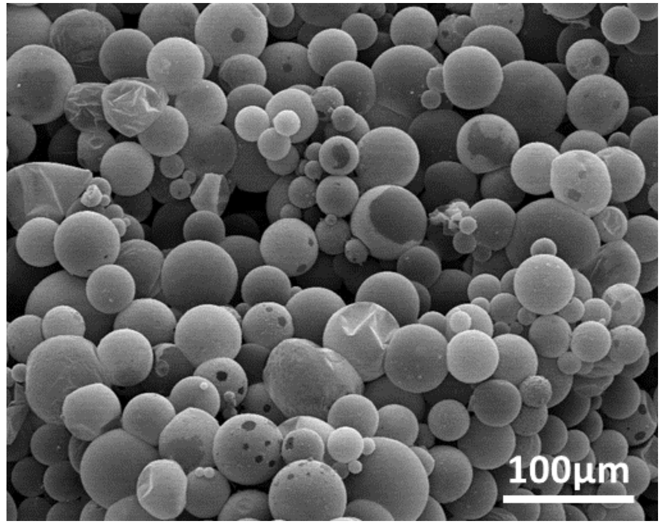
90 - 95% porosity is necessary to achieve large enough surface T-swing. Approx. half the volume is within spheres, half is interstitial.



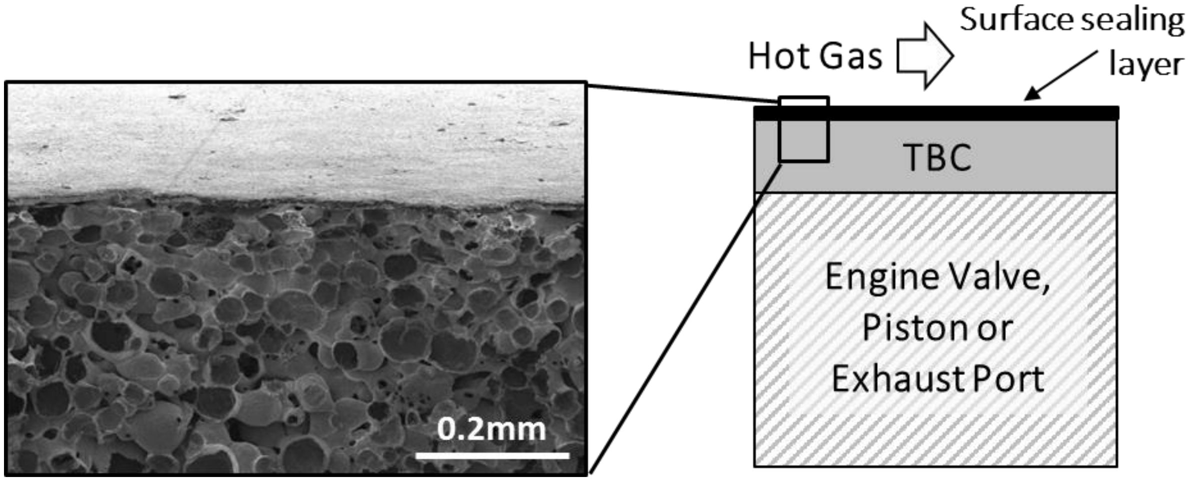


Approach





HRL has developed hollow nickel-alloy microsphere TBCs with an average diameter of 30 - 50µm and 1 - 2µm shell thickness. These microspheres can be sintered together to form high-temp metal matrices with over 90% porosity

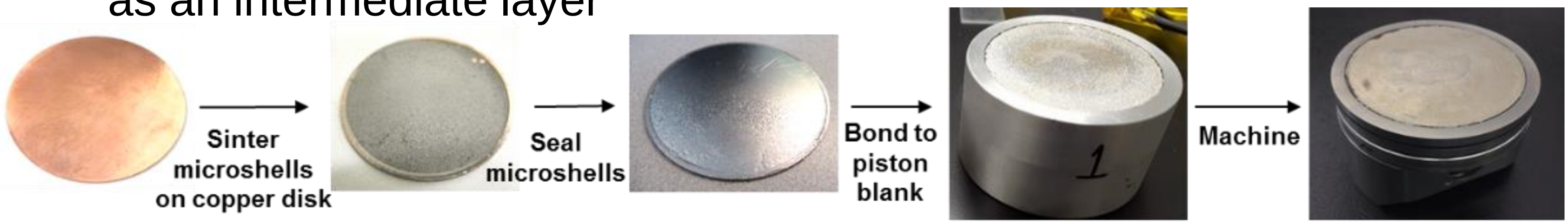


Microsphere TBCs can be applied using dry molds, slurries, or air spraying. The surface must be sealed to avoid ingress of hot combustion gasses and unburned fuel vapor.

Approach

A process was created for applying the microsphere-based insulation to aluminum components, such as the pistons.

- Microspheres sinter to form insulation layer at ~900˚C, but aluminum piston would melt at ~500˚C, so a bonding layer (copper disk) is used as an intermediate layer



Steel components, such as the valve faces and within the exhaust port inserts within the cylinder head are simpler. The Ni-alloy microspheres can sinter directly to the steel.

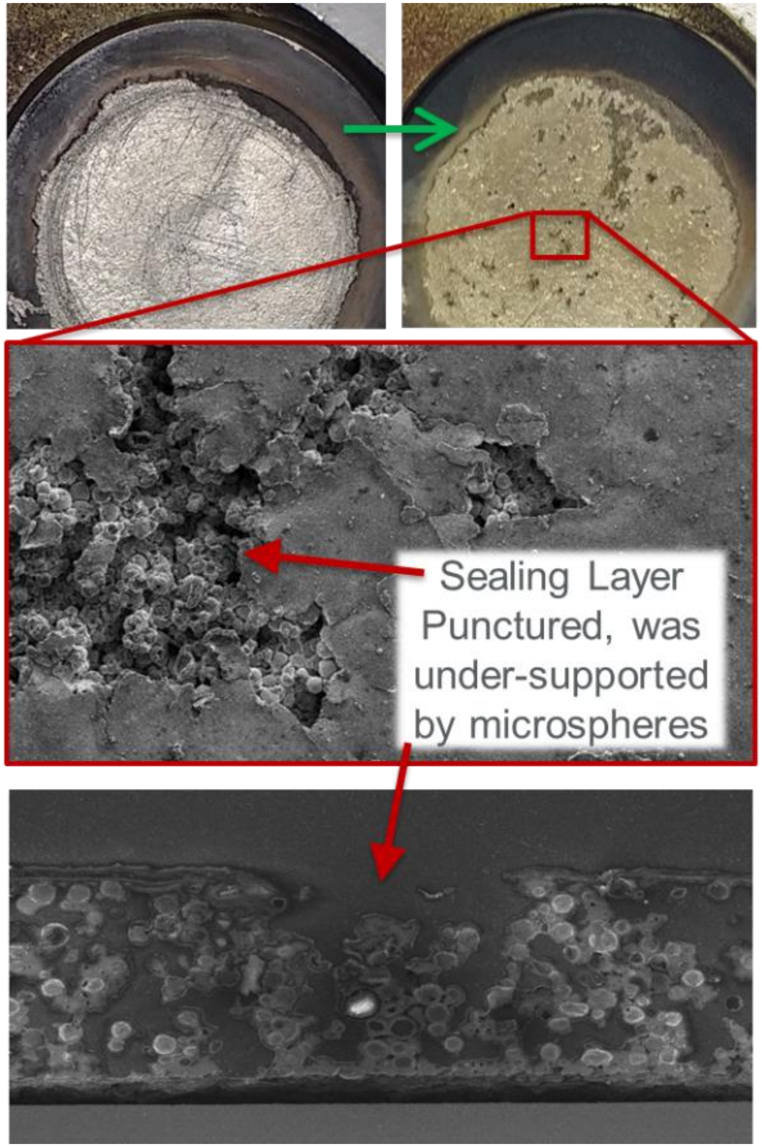
- Steel Exhaust port inserts were coated and sintered, then placed in cylinder head mold for casting.

Progress – Coated Valves

Intake and exhaust valves were coated with the microspheres and a 2.5µm Ni foil as the sealing layer. All of these components showed that the sealing layer was prone to puncture in many spots, some of which coincided with pre-test visible irregularities.

Cross-sections revealed the microsphere structure survived the pressure and temperature intact, but the foil layer was poorly supported by it in the breached spots. The cause was an uneven packing density throughout the microsphere layer.

The key to a successful porous insulation coating is a robust, impenetrable surface sealing layer.

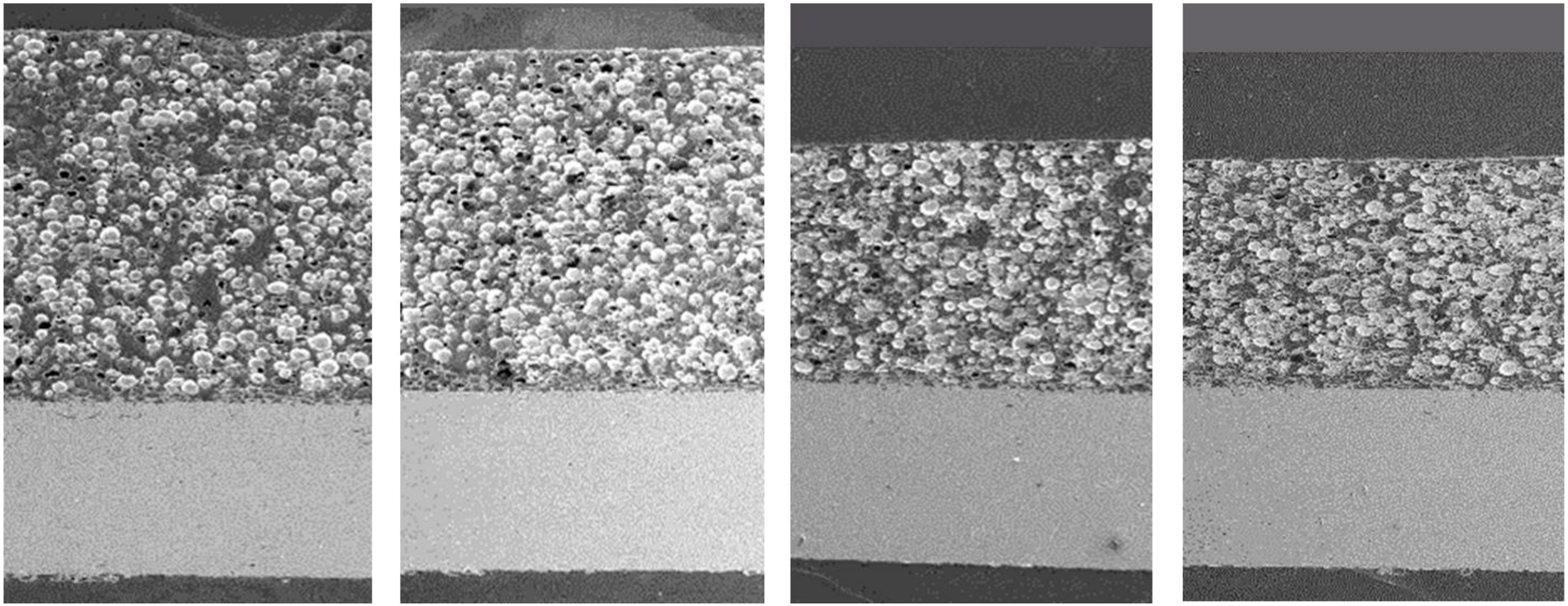


Progress – Microsphere Structure

Pressure was applied to the top surface of the microsphere layer during sintering to attempt to improve packing density and create a more uniform microsphere layer. ~30 kPa appears to be ideal without excess crushing.

Greater compaction will result in higher density and smoother surface to enhance surface sealing.

9 kPa | 18kPa | 27 kPa | 36 kPa



Progress – Coated Pistons

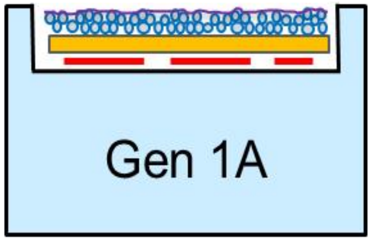
Two generations of aluminum pistons were tested in the first year. The learnings from the first were applied to creating the second.

Generation 1A piston microsphere layers were created in a similar manner to the valves, and thus had many of the same permeability issues. Additionally, they had poor bonding between the copper disk and aluminum pistons, which lead to the separation of the part along this seam.

Generation 1B incorporated improvements in microsphere packing shown previously, as well as a copper pocket design to seal the sides of microsphere layer. Better brazing techniques used for adhesion, but a bubble still formed between Cu & Al.

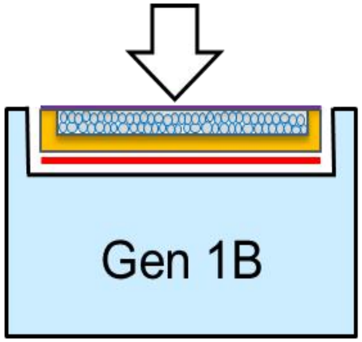
In parallel, steel pistons are being procured to minimize risk of aluminum bonding to allow direct evaluation of the thermal barrier materials

Loose Microsphere Surface, 2.5μm Sealing Foil, Copper Disk



Brazing with Zn-Al filler metal strips No pressure applied.
Failed

Compacted Microsphere Surface, 2.5μm Sealing Foil, Copper Pocket

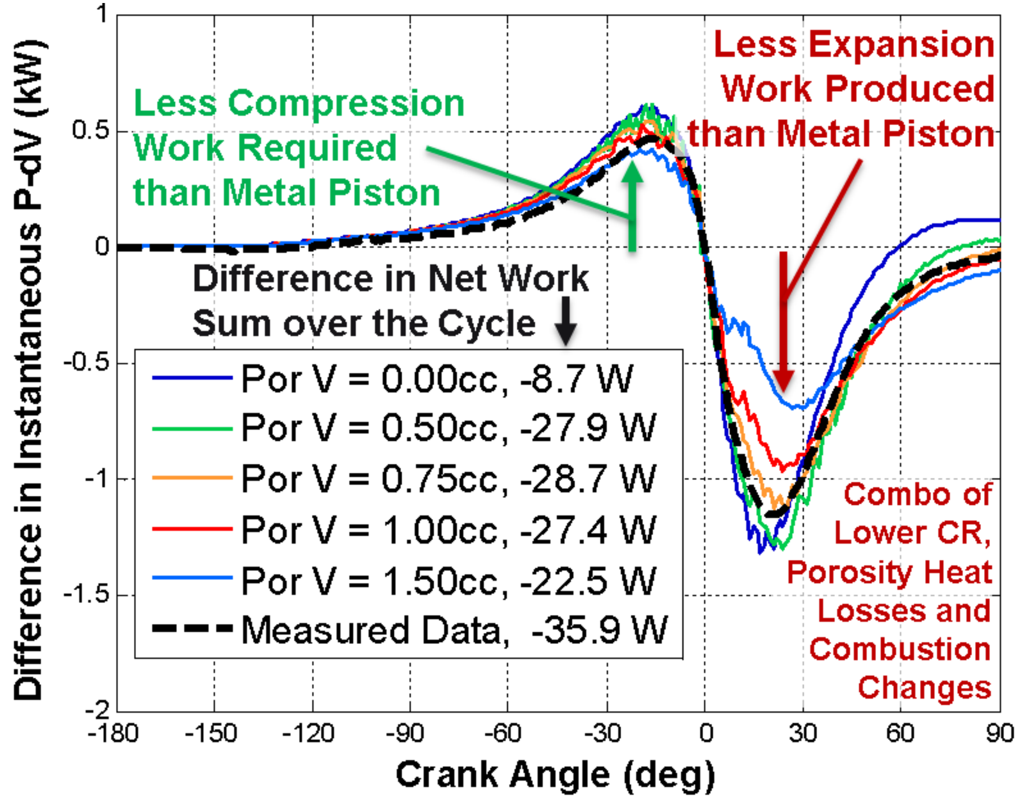


Diffusion brazing with Zn foil. No flux. Pressure applied.
Limited Success

Progress – Modeling Results

All heat-transfer effects described previously are captured by modeling efforts.

- Porosity heat losses captured by including high-heat-transfer combustion chamber sub-volume, simulating high surface-to-volume ratio in interstitial volume. An effective orifice diameter into this volume used to capture the permeability. The large decrease in indicated work after TDC is due in part to the porosity heat losses.
- Porosity fuel trapping affects total amount of heat released and time at which it is released. This loss also appears after TDC.
- Poor bonding between Cu disk & Al piston captured as thermal resistance, increasing average surface T and compression gas heating. This is masked by lower CR due to additional volume in coating interstitial voids

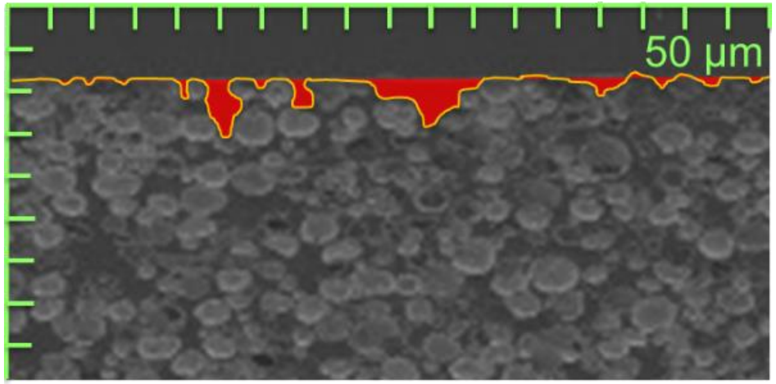


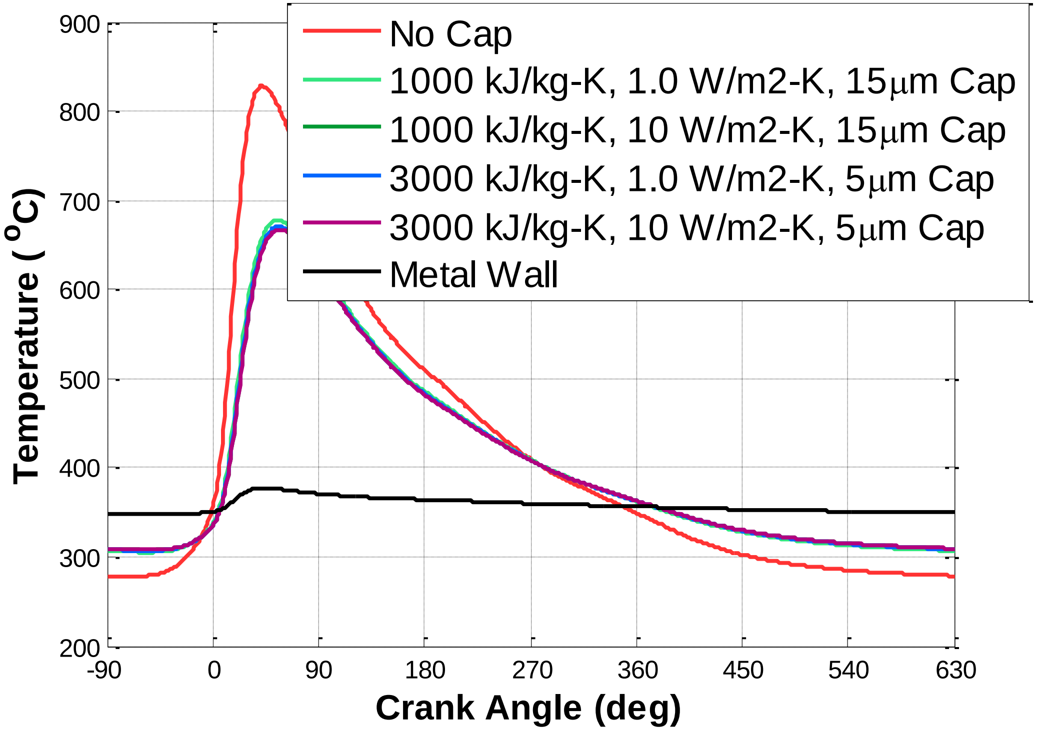
Progress – Modeling Results

Performance of the coating with the sealing layer is highly dependent on the mass and heat capacity of the sealing layer. Essentially, the surface temperature swing is only possible if the “thermal inertia” of the insulation surface is low enough, and if this surface is not anchored to a heat sink.

Thermal Conductivity of the sealing cap has no impact on temperature-swing, but the heat capacity and cap thickness (total mass) have a 1:1 trade-off.

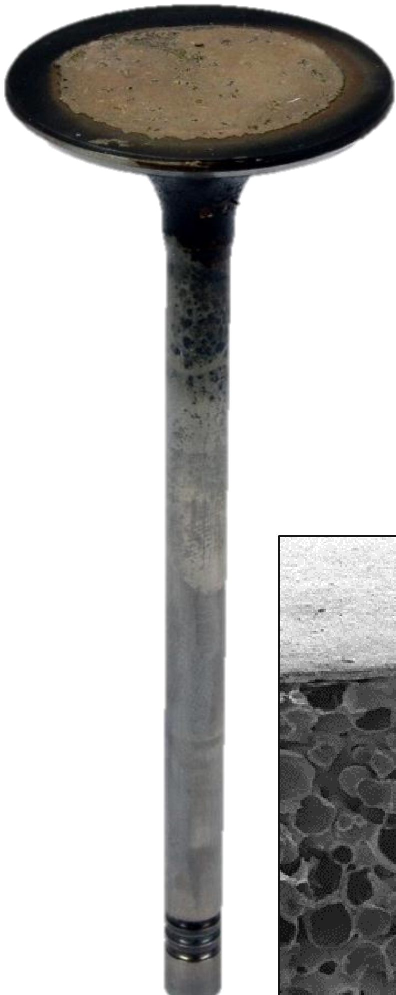
Lower mass and heat capacity enable a thicker sealing cap.

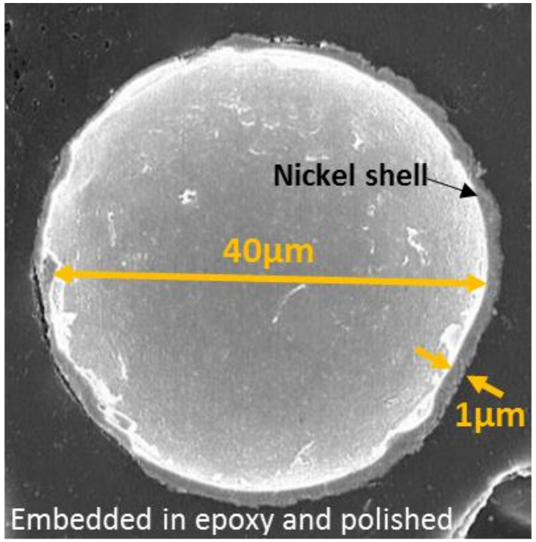


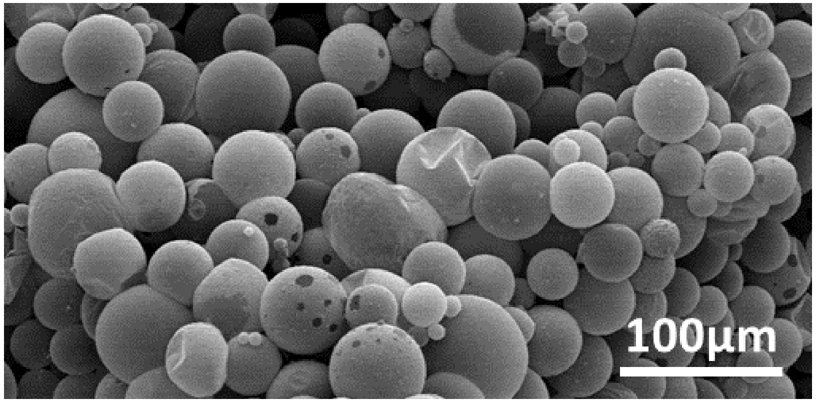


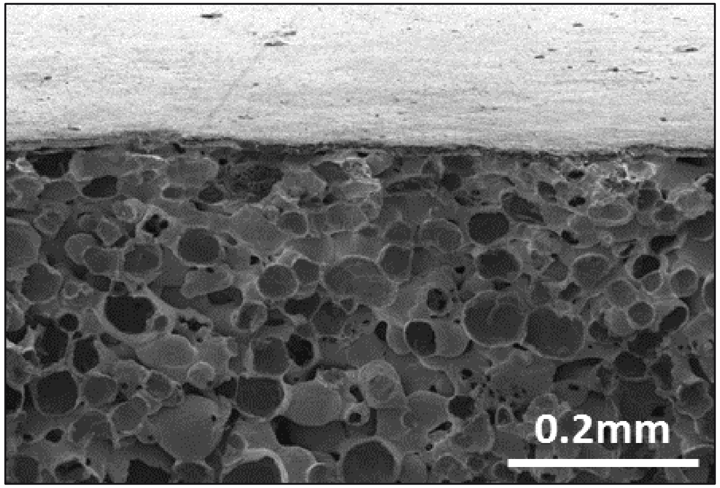
Response to Previous Comments

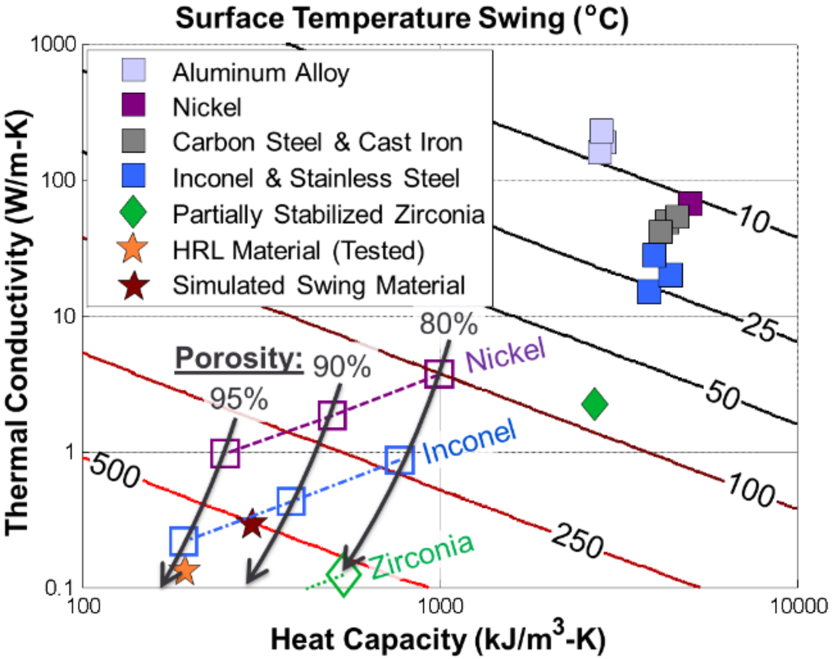
This is the first Annual Merit Review for this project











Collaboration / Coordination

HRL Laboratories - Primary Investigator (Malibu CA)

GM Research - Subcontractor (Pontiac MI)

Multiple other US companies have been engaged for different parts of this program

- Mass Production of Microspheres for use in coating – **3M**
- Design and production of steel pistons – **Federal Mogul**
- Discussions running for alternate sealing layer solutions – **Agreements pending**

Remaining Challenges

1. Further work on microsphere structure and sintered-layer properties is necessary for temperature-swing performance <u>AND</u> impermeability.
2. Alternate sealing layer concepts are being explored to ensure impermeability and durability.
3. Bonding techniques to aluminum components need to be refined to ensure a robust, reliable solution with desired temperature-swing range.
4. Steel pistons are being sourced as an alternative solution for insulating the piston.
5. Capability for more complicated surface geometries must be developed and refined.
6. Processes must be scaled or adapted to achieve mass-production capacity, performance, and cost targets.

Future Research

To address the challenges stated previously, we plan on:

1. Using various techniques such as the slurries, selective microsphere size filtering, physical compaction, and pressurized spraying to achieve better microsphere structure and packing densities.
2. The steps taken above should help to better support the sealing layer while maintaining high levels of porosity below it, alternate sealing layers formed from ceramic or metallic slurry impregnation, selective surface melting/compaction and polishing techniques are being investigated.
3. Additional brazes, piston alloy changes, dry diffusion bonding, capturing the insulating layer within the piston casting, and bonding process changes are being explored to address aluminum bonding.
4. Sintering insulation to steel components will be used to validate thermal barrier solutions, may allow other avenues of improvement.
5. Alternate methods for constructing the insulating layer around molds, shaping it after sintering, maintaining sealing layer integrity across curvature, and attaching to curved surfaces are all being explored.
6. Corporate partners and internal manufacturing assets are being engaged to create and evaluate inclusion of insulation in production.

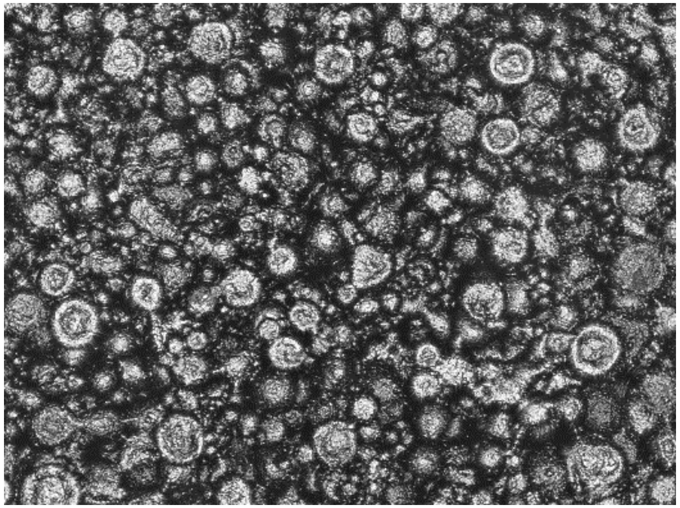
FY18-FY19 proposed work is subject to change based on funding levels.

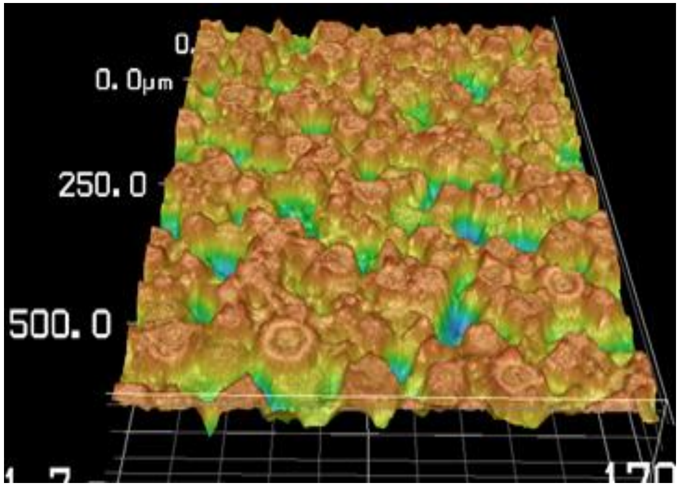
Future Research – Sealing

Variations in the pressure applied during sintering, selective filtering and layering of the microspheres, and forming techniques for the layer can all substantially reduce the surface roughness.

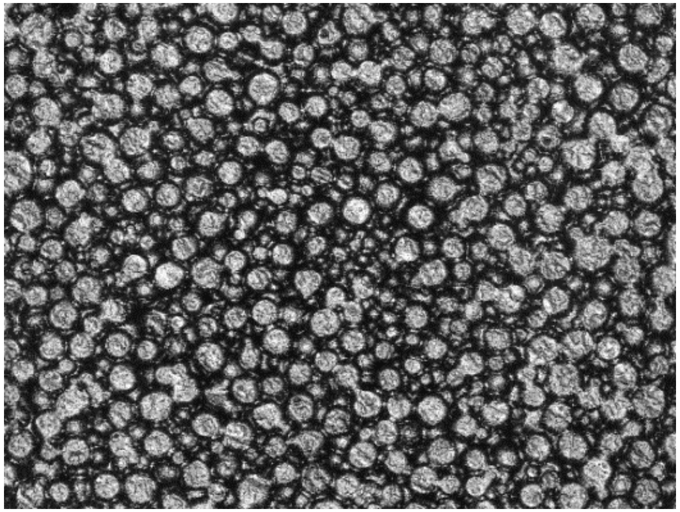
This will greatly reduce the gaps that a sealing layer will need to bridge or fill.

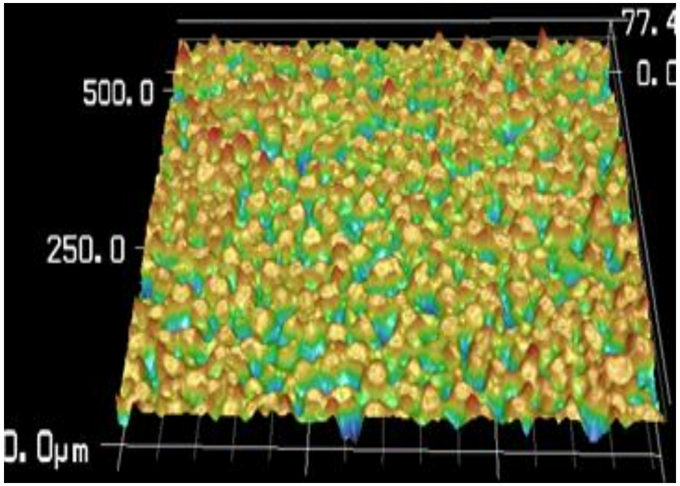
9 kPa Sintering Pressure, Large Ø Sphere Top Layer





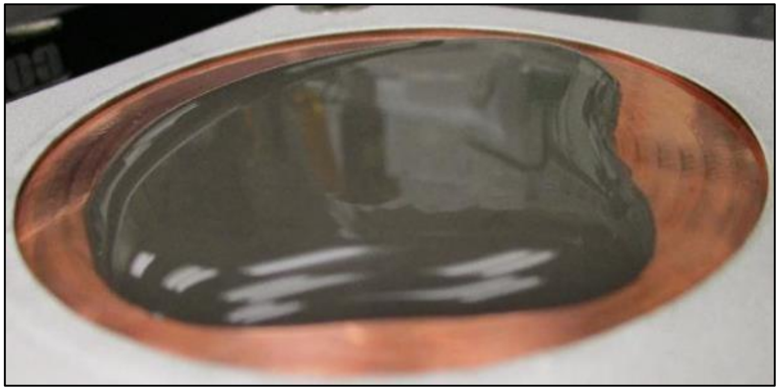
30 kPa Sintering Pressure, Small Ø Sphere Top Layer

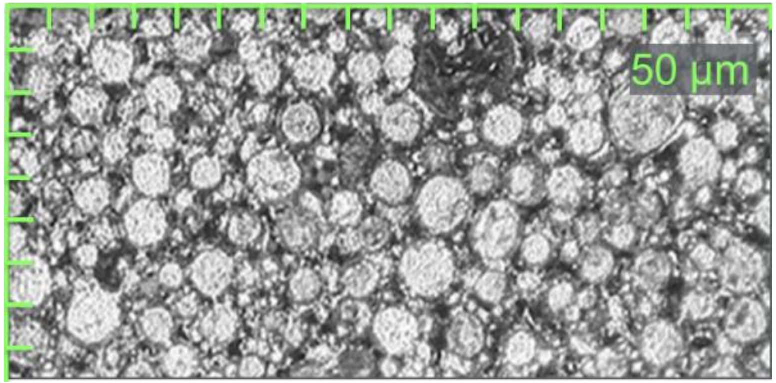




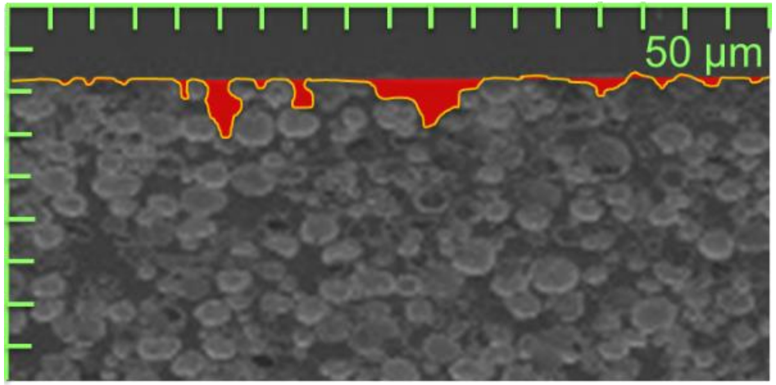
Future Research – Sealing

To further improve the consistency of the microsphere structure, slurries involving a liquid suspension of the microspheres and possibly a binder are being investigated. These should improve packing, ensure an even thickness, & prevent static clumping of the microspheres.



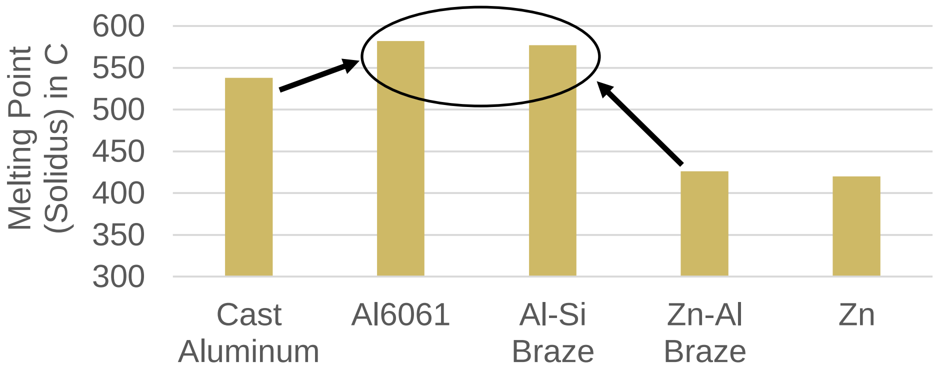


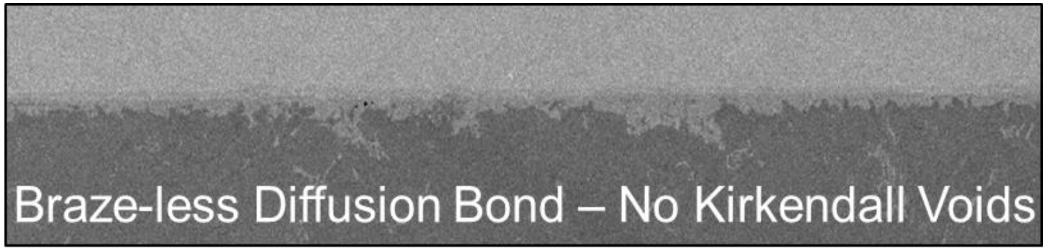
As we improve the surface finish of the layer, it becomes possible to fill the valleys and crevices in the outward surface with a very thin, low-mass metallic or ceramic substance. Minimizing the mass of the sealing layer is very important to preserving the temperature-swing performance of the insulation.



Future Research – Bonding

Experimentation with Zinc-less brazes and Copper-Aluminum diffusion bonding without braze are being performed to avoid the Kirkendall voids observed as bonding failure cause in previous pistons.





We are working with a supplier to procure steel pistons. This will allow us to sinter the Ni microspheres directly to the piston, avoiding the bonding issues. Once the bonding concerns are removed, we can evaluate the performance of the insulation directly, without relying on modeling work to characterize the various loss mechanisms.

Summary of Work

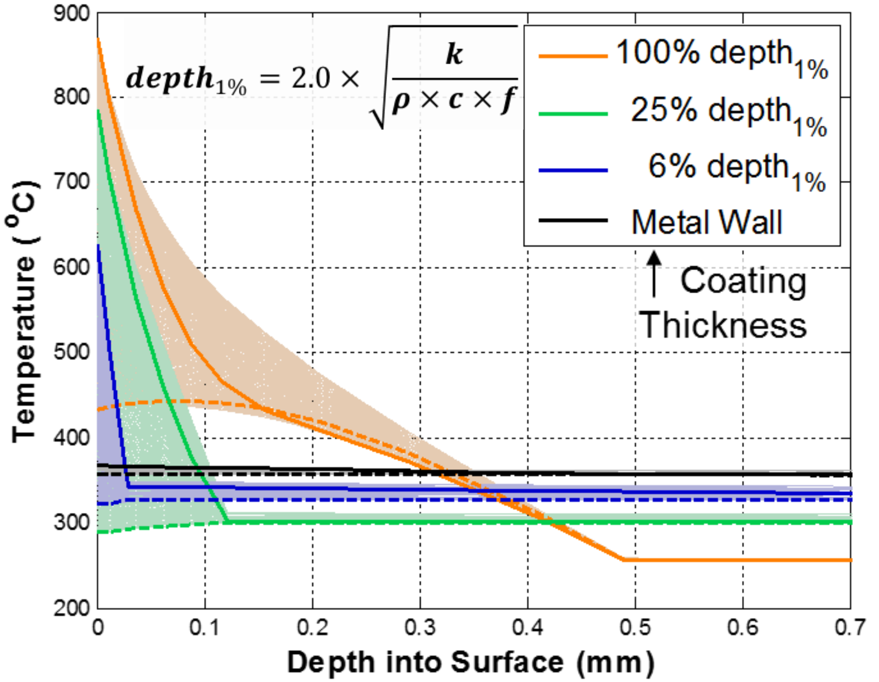
- The microsphere-based insulating material is meeting the target material properties of 0.2 W/m-K Conductivity and 0.2 MJ/m^3-K for temperature-swing insulation.
- The microsphere insulation layer successfully survived the in-cylinder environment with no observed degradation to the microsphere structure.
- Drastic improvements in the impermeability of the sealing layer have been made and alternative processes are being pursued to eliminate interstitial gas penetration.
- Bonding to current aluminum pistons has been problematic, but work continues to solve the issues in parallel to thermal barrier materials development on steel components.
- Analytical tools have been developed and validated allowing accurate assessment of potential design solutions.

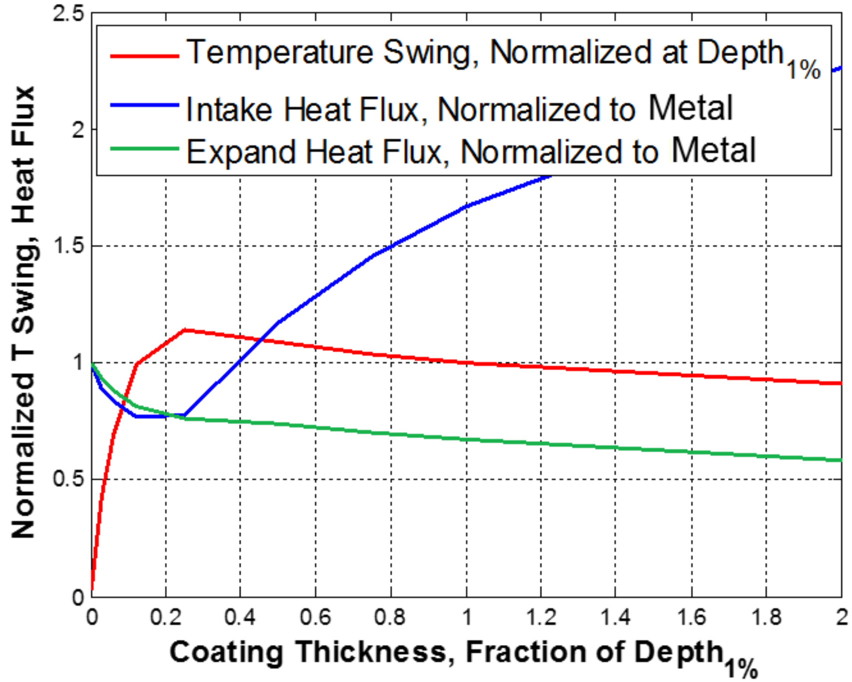
Technical Backup Slides

Ideal Coating Depth

A representative "Depth$_{1\%}$" was defined based on the material properties and cyclic engine frequency to describe the depth into a material at which the inter-cycle temperature swing has decayed to 1% of it's surface value.

The ideal coating thickness is 25% of the depth$_{1\%}$ to minimize heat loss during expansion and the intake stroke, effectively balancing heat losses off the front and back of the coating to allow maximum temperature swing while minimizing the intake heat transfer in comparison to the baseline metal wall.



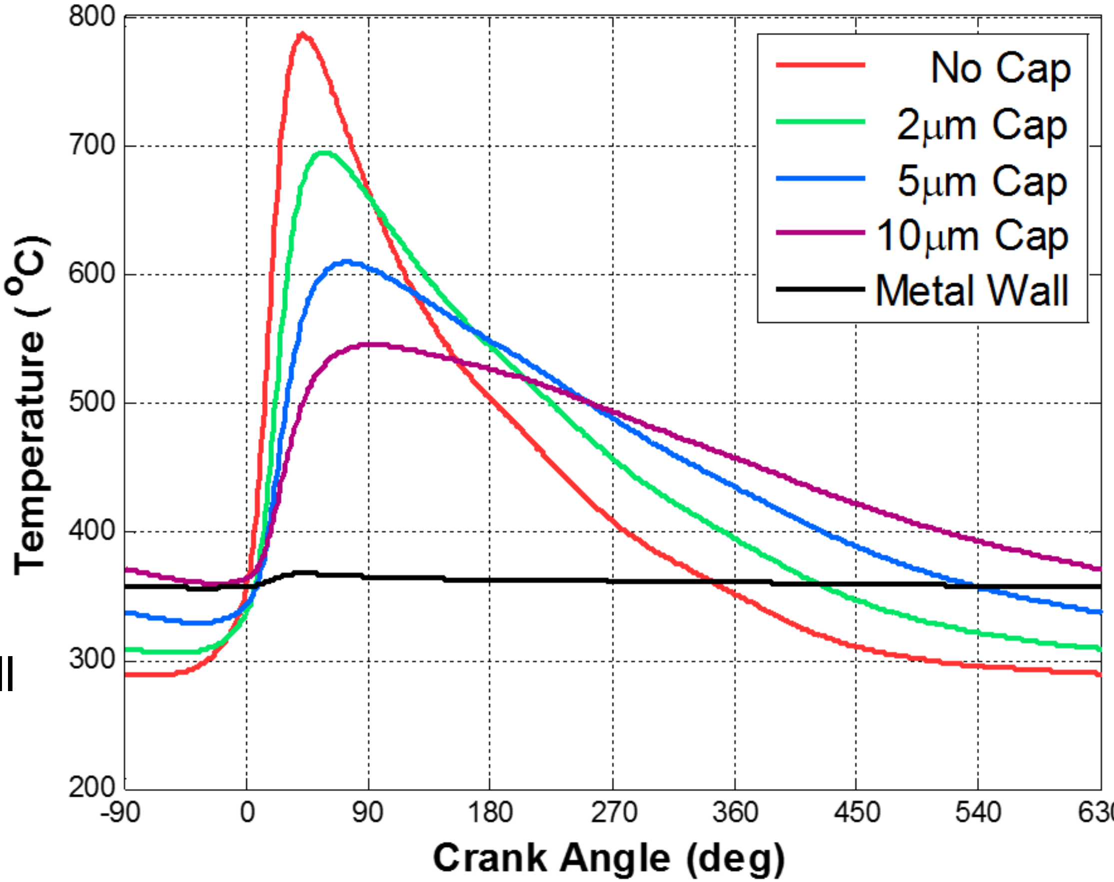


Influence of Sealing Cap

Highly porous coatings, especially with a large portion of open-cell porosity such as the void spaces between packed microspheres spheres, will require an impenetrable sealing layer to prevent permeable porosity losses, which impacts the surface temperature swing by concentrating mass where it is most detrimental.

Thicker metal sealing caps substantially dampen the surface T swing while increasing the wall temperature during intake and compression; These effects are somewhat mitigated by adjusting the insulating layer thickness beneath the sealing layer

Ultimately a very thin or low-mass sealing layer is critical to the overall coating performance



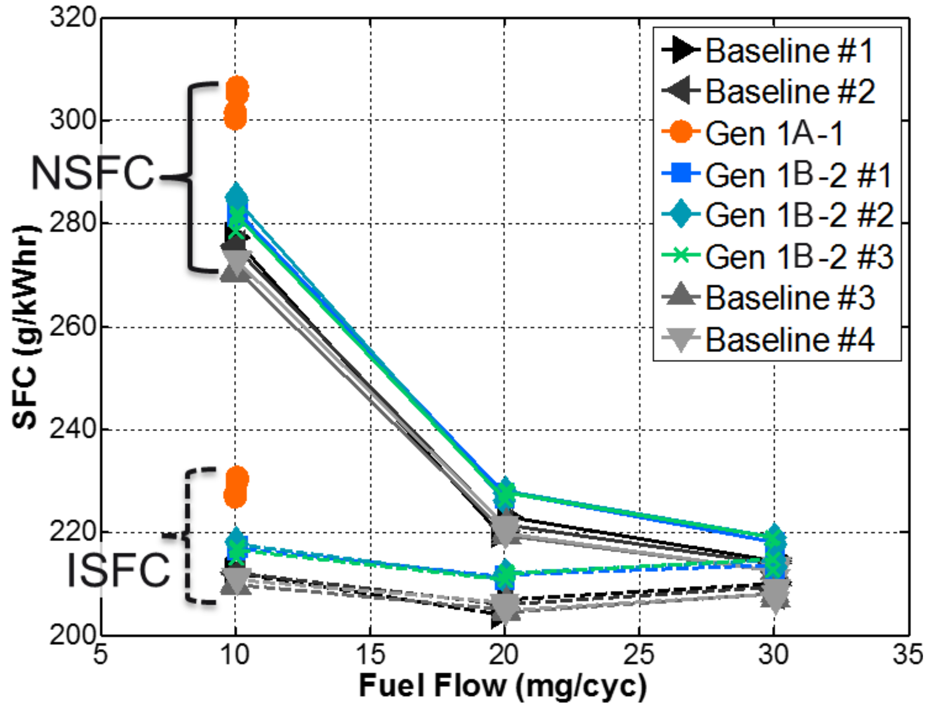
Progress – Coated Pistons

Fuel consumption for Gen 1A was 10% worse than the aluminum baseline, while Gen 1B was only 2% worse due to various permeable porosity losses.

Permeable porosity, such as the interstitial volume within the microsphere layer, can create a few avenues for efficiency losses in an engine.

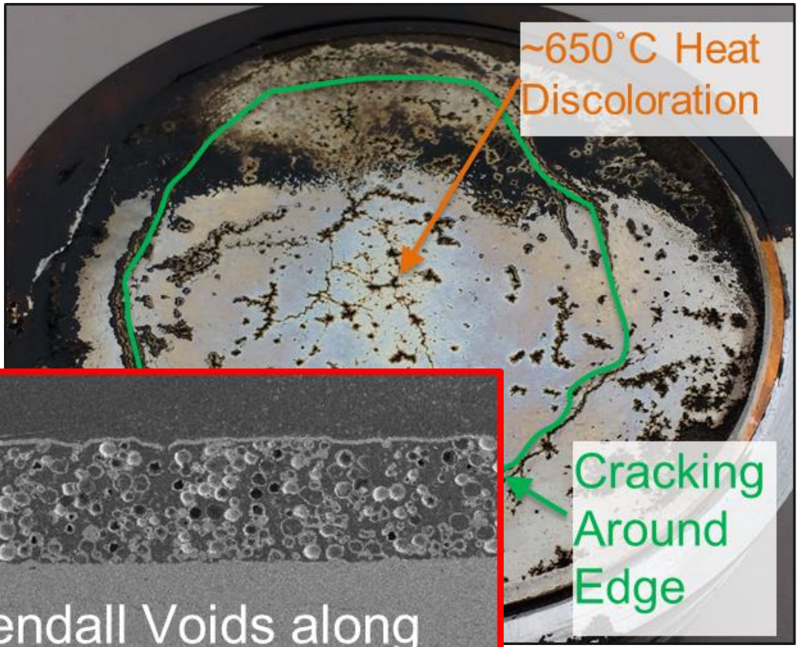
- It will drastically increase the surface area of the piston and thus the heat transfer, especially as pressure increases during compression and combustion.
- It provides a volume that is relatively shielded from combustion where unburned fuel can get trapped.
- Greater in-cylinder volume results in a lower compression ratio.

These losses highlight the need for robust surface sealing to prevent interstitial gas penetration.

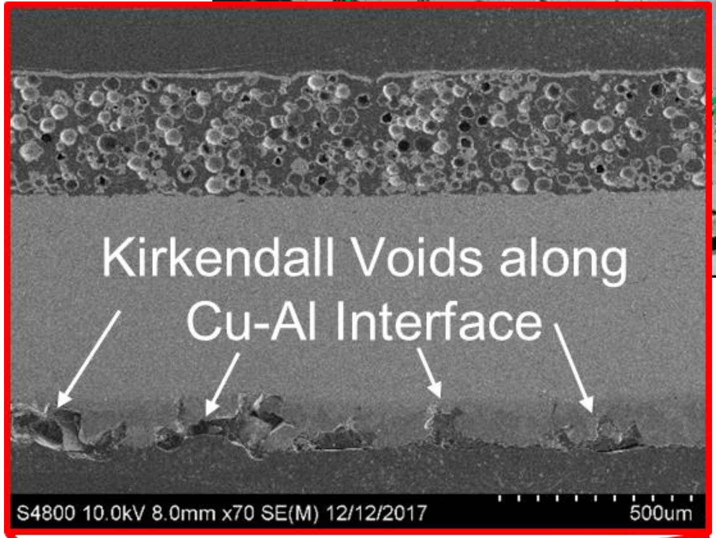


Progress – Coated Pistons

Piston 1A-2 had very poor bonding from the beginning of testing, while the center of Piston 1B-2 appears to have bubbled up after the first day. Both of these will increase the average surface temperatures by essentially burying an air gap between the insulation and piston.



Kirkendall Voids formed as Zn from braze diffused into Al piston and Cu disk, leaving holes forming weak plane.



Use of Zn-free braze on Al Piston or Steel Piston (direct micro-sphere sintering) could solve this bonding problem.